METHOD AND APPARATUS FOR WRITING
MULTIPLE TRACKS OF AN OPTICAL DISK

Field of the Invention

The present invention relates to optical disk
5 drives which can read and write optical disks. More
specifically, the present invention provides a multi-
beam optical system for simultaneously writing multiple
tracks of an optical disk.

Background of the Invention

10 Current writable optical disk technologies
include several write-once technologies, such as CD-
Recordable (CD-R) and DVD-Recordable (DVD-R), as well
as re-writeable technologies, such as CD-Re-writeable
(CD-RW), DVD Re-writeable (DVD-RW), and DVD-RAM.

15 Data is typically recorded on writeable
optical disks by using a writing beam having a higher
power than is used for reading. The media for use with
optical disk writers typically includes a recording
layer, made of a material which changes its optical
20 characteristics in response to the presence of the beam
from the high power laser. The high power laser is
used to create "pits" in the recording layer which have
a different reflectivity than surrounding areas of the

disk, and which can be read using a lower power reading beam.

Because in most previously known optical disk systems the data are read from or written to the disk serially, i.e. one bit at a time, the maximum data transfer rate for an optical disk reader is determined by the rate at which the pits pass by the pickup assembly. Because the linear density of the bits and the track pitch are fixed by the specification of the particular optical disk format, the data transfer rate of optical disk readers is limited by the rotational speed of the disk itself. However, high disk rotational speeds place increased demands on the optical and mechanical subsystems within the optical disk player, create greater vibration, and may make such players more difficult and expensive to design and manufacture.

Furthermore, in recording systems, the minimum energy required to form a mark of a given length is determined by the chemical and thermal properties of the recording disk medium. The laser energy impinging on the mark area is proportional to laser power and inversely proportional to disk rotational speed. Thus, for a given laser power, there is a practical upper limit to the disk rotational speed during recording.

A cost effective alternative to increasing the disk rotational speed to provide faster optical disk drives is to read or write multiple data tracks simultaneously, as described in commonly assigned U.S. Patent No. 5,426,623 to Alon et al. In accordance with the methods and apparatus provided therein, for example, ten adjacent data tracks may be read simultaneously. Thus, even if the disk is rotated at

only 8x the standard speed, the capability to read ten tracks simultaneously provides the equivalent of a 80x drive.

It would therefore be desirable to provide an
5   optical drive that achieves improved writing speeds by writing data to multiple tracks of an optical disk simultaneously.

Summary of the Invention

An optical disk system constructed in
10 accordance with the present invention preferably employs a number of laser diodes capable of operating at selectable power levels to generate: a low power light beam in a read mode of operation, a high power light beam in a write mode of operation, and an
15 intermediate power light beam in an erase mode of operation. An optical pickup directs the light beams from the multiple laser diodes to the corresponding tracks of the optical disk, ensuring the light beams are in focus and tracking the proper tracks. The beams
20 are properly spaced apart to prevent interference between data written by the multiple beams. A processor, either a specially programmed general purpose processor or an application specific integrated circuit, controls the power supplied to the laser
25 diodes according to the selected mode.

Brief Description of the Drawings

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed
30 description of the preferred embodiments, in which:

FIG. 1 is a schematic block diagram of a optical disk drive using multiple beams to read and

write multiple tracks of an optical disk simultaneously;

FIG. 2 shows illustrative temperature profiles when writing to a CD-RW type optical disk with
5 one and two writing beams;

FIG. 3 shows illustrative temperature profiles when writing to a DVD-RW type optical disk with one and two writing beams;

FIG. 4 shows illustrative temperature
10 profiles when writing to a DVD-RW type optical disk with up to three writing beams;

FIG. 5 shows the effect of write beam spacing on pit width;

FIG. 6 shows the results of a simulation of
15 writing pits on adjacent tracks of an optical disk; and

FIGS. 7 and 8 show illustrative write beam geometries that prevent interference between pits when writing to nearby tracks.

Detailed Description of the Invention

20 Referring to FIG. 1, multibeam optical disk drive 10 is described. Laser diodes 11a-c generate illumination beams 12a-c. Beams 12a-c are reflected by prism mirror 14 and pass through beam splitter 15. Beams 12a-c are then collimated by lens 16 and
25 reflected by mirror 17 toward objective 18, which focuses the beams onto a surface of optical disk 19. Because the severity of aberrations introduced by the optical components shown in FIG. 1 increase with a beams distance from the optical axis of the component,
30 it is desirable to minimize the spacing between beams 12a-c. Motor 20 spins optical disk 19, and various servo systems and actuators move one or more of the components of FIG. 1 to access different areas of

optical disk 19, and to keep beams 12a-c focused on, and in alignment with, the appropriate tracks of optical disk 19.

Beams 12a-c are reflected from a data-bearing
5   structure in optical disk 19 and modulated by the data recorded there. The reflected, modulated beams again pass through objective 18 and are directed back to collimator 16 and beam splitter 15 by mirror 17. Beam splitter 15 directs the returning beams through lens 21
10 onto detector 22, having a plurality of photo-detector elements. Each photo-detector element detects the modulation of a corresponding reflected light beam and produces a corresponding electrical signal. Processing circuitry 13 extracts data from the signals to read the
15 data from a track of the optical disk. Processing circuitry 13 also modulates laser diodes 11a-c when writing to optical disk 19. Additional signals output by detector 22 may be used to detect errors in the focus and tracking of the optical disk drive.
20   A multi-beam optical disk drive, as described above, is capable of achieving very high speeds when reading an optical disk. A seven beam reader, for example, which rotates the disk at 10x standard speed, would provide a data rate equivalent to a 70x drive.
25 Thus, simultaneously reading multiple tracks of an optical disk provides significant increases in data reading rates at relatively low spindle speeds, as compared to optical systems that read a single track.

It should be noted that as used herein, a
30 data track is a portion of the spiral data track of a typical optical disk which follows the spiral for one rotation of the disk. Thus, a drive capable of reading multiple data tracks simultaneously reads several such portions of the spiral data track at once. For disks

having multiple concentric spiral tracks, a data track would refer to a corresponding portion of one of the concentric spiral tracks. For optical disks having concentric circular tracks, a data track would refer to

5 one such circular track.

In addition, simultaneously is used to mean concurrently, although not necessarily starting and stopping at the same time. So, for example, writing two tracks simultaneously means that at some time two

10 tracks are being written at the same instant even though writing did not start or end at the same time for both tracks.

The laser diode used in an optical disk writer is capable of generating a higher power beam

15 than the laser diode of an optical disk reader. For example, while reading may require a light beam having a power of 0.5 mW, writing data to an optical disk may require a light beam having a power in the range of 12 to 14 mW, depending upon the specific optical disk

20 technology employed. Many optical disk writers also may produce a light beam having an intermediate power used to erase areas of the writeable optical media. Such a light beam may, for example, have a power of 10mW. The power of the beam is modulated to

25 selectively read, erase, and write corresponding pits on the optical disk that may be subsequently read by an optical disk reader.

In accordance with the present invention, a multi-beam optical disk reader is provided that is

30 capable of simultaneously reading multiple tracks of data during a read mode of operation and which is also capable of writing multiple tracks of data during a write mode of operation.

It is assumed during the following description that optical disk 19 is a re-writeable optical disk, such a DVD-RAM, or DVD-RW disk. It will be apparent from the following description, however,

5 that optical disk 19 also may be, for example, a CD-ROM or DVD-ROM disk, where it is desired to use only the read mode of operation of the optical system.

Processor 13, which may be a suitably programmed general purpose microprocessor or digital

10 application-specific integrated circuit, determines whether the optical system is to operate in read mode or write mode, and issues commands to adjust the power supplied to laser diodes 11a-c. Accordingly, when multiple tracks are being read during read mode,

15 processor 13 causes laser diodes 11a-c all to be continuously energized to produce light beams with sufficient power to permit reading multiple tracks on optical disk 19. During the write mode of operation, when data is being written to optical disk 19,

20 processor 13 causes laser diodes 11a-c to output beams with sufficiently high power for writing data to optical disk 19, modulated according to the data being written. If desired, processor 13 may also provide an erase mode of operation, for use with re-writable

25 optical media such as DVD-RAM disks.

Optical storage systems, such as CD and DVD, rely on the geometry of marks on the optical media for proper operation. For example, data is encoded by the length and spacing of the marks; whereas tracking

30 relies on the width and symmetry of the marks. It is therefore critical that marks on optical media have the proper size and shape. This presents some problems when writing multiple beams simultaneously.

The shape of written marks depends on the temperature profile during writing and the specific temperature thresholds for writing and erasing (in the case of RW media) of the optical media. The

5 temperature profile during writing depends, in turn, on the energy distribution of the laser beam and the thermal conductivity of the media. The latter depends on the composition and layer structure of the media.

CD-R type disks have a dye layer and a metal

10 layer sandwiched between two polycarbonate layers. When writing to a CD-R, a laser beam focused on the metal layer causes localized heating in the surrounding materials. This raises the temperature to approximately 600°C, causing an irreversible chemical

15 change of the dye. Areas in which the dye has been changed reflect reading beams differently than areas in which the dye has not been heated, enabling the data to be read.

A CD-RW or DVD-RW has a slightly more complex

20 structure, including an outer polycarbonate layer, and a writing structure including a protective layer, an active layer, another protective layer, and a metal layer. When writing to such a disk a reversible change in the active layer is used to record the data. A

25 common active layer is made of a Ge-Sb-Te material which undergoes a phase change when heated. An amorphous mark is made by heating the material to 600°C followed by rapid cooling. The mark is "erased" by heating to a temperature of about $200°C < T_{erase} < 600°C$,

30 which changes the material back from an amorphous to a crystalline form. The amorphous and crystalline forms possess sufficiently different optical properties that an optical disk reader is able to read data previously written to the disk.

For current types of recordable media, writing occurs at about the same temperature, e.g., 600°C, and deviations from the ideal writing temperature produce similar results. As noted above,

5 the size and shape of the pits or marks recorded on an optical disk is critical to the proper operation of an optical disk drive. Heat from a writing beam diffuses through the volume of an optical disk so that heating is not limited to areas directly illuminated by the

10 writing beam. If the diffused heating is sufficient to cause changes in the recording layer away from the writing beam, the resulting marks may be oversized or misshapen, and may not be readable by an optical disk reader.

15 The amount of diffuse heating depends on the structure of the disk, the thermal diffusion coefficient (DT) of the materials in the disk, and the length of time heat is applied. Typical re-writeable media have active and protective layer approximately

20 0.01 to 0.1 mm thick and an outer plastic layer of about ~1 mm. The effective value of thermal diffusion coefficient depends on the actual multi-layer structure of the specific optical disk media, but for typical media, it is on the order of approximately 10^{-2} cm^2/sec.

25 The typical writing time for one mark is about 100 nsec. During this time, the radius of the thermal diffusion zone is about 0.3 μm as given by Equation (1).

$$\sqrt{DT \times t} \tag{1}$$

30 Where DT is the coefficient of thermal diffusion, and t it the time. The size of the thermal diffusion zone effectively puts a lower bound on how close together adjacent marks can be written. For example, the

writing of a given pit is highly influenced by the temperature distribution within the disk, which spreads out from the previously written pit as described in "Ten-Year Overview and Future Prospects of Write-Once

5 Organic Recordable Media", by E. Hamada, Y. Takaguchi et al, Japanese Journal of Applied Physics, v.39 (2000), pp.785-788. Part 1, No.2B. The corresponding safe distance between the end of a previous pit and the beginning of a pit being written is referred to as "the

10 minimum inter-pit interval" (MIPI). As an example, the MIPI for a CD-R is 0.83 µm, whereas the MIPI for a DVD-R is 0.4 µm. Ongoing developments in optical disk technologies promise finer track pitches, and correspondingly smaller MIPIs, in the future.

15   Under typical conditions, the inter-pit spacing on an optical disk is greater than the MIPI given by the Hamada article, and diffuse heating due to a single writing beam is not sufficient to cause adverse changes in areas surrounding a pit being

20 written. However, this is not true when writing with multiple beams. Because the radius of the thermal diffusion zone is approximately the same order of magnitude as the track pitch of typical optical disks, writing on adjacent tracks might deteriorate the shape

25 of written marks due to mutual influence of their temperature distributions.

       An approximation for the minimal distance needed between simultaneously written marks on adjacent tracks, may be estimated from temperature distribution

30 in the optical disk immediately following a write operation. The temperature profile may be approximated by the Green's function for a point source of heat on a two-dimensional surface, given in Equation (2).

$$T(x) \propto G(x,t) = \left(\frac{2}{\pi\tau}\right)e^{\left(\frac{-x^2}{\tau}\right)} \tag{2}$$

Where $T(x)$ is the temperature distribution at the end
of a 100 nsec writing pulse; x is the radial distance
from the center of the mark; τ = 4×DT×t; and t = 100

5   nsec.

The resulting temperature distribution has a
shape like that of curve 26 of FIG. 2. As shown, the
temperature peaks well above 600°C at the center of the
writing beam, and gradually diminishes with distance.

10   When two point sources are used to write simultaneously
on adjacent tracks separated by a distance, d, the
resultant temperature distribution can be estimated by
superposing two Green's functions as shown in Equation
(3). The resulting temperature distribution has a

15   shape like that of curve 28 of FIG. 2

$$G2(x,t) = G(x - \frac{d}{2},t) + G(x + \frac{d}{2},t) \tag{3}$$

For a typical CD-type optical disk the
resulting temperature profile is shown in FIG. 4, in
which curve 42 corresponds to writing a single track,

20   and curve 44 corresponds to writing on two adjacent
tracks simultaneously. As shown, when two writing
beams are spaced at the track pitch of CD media, e.g.,
at about 1.6 microns, the portion of curve 44 for which
T > Twriting is broader than it is for curve 42. This

25   means that the written marks are broader when writing
with two beams than when writing with one beam. Also
of note is that the increase in pit width is not
symmetrical about the track centerline. This in turn
may adversely impact the tracking ability of an optical

disk reader. Moreover, wider pits may result in increased crosstalk between adjacent tracks.

The situation is worse for DVD-type media. As shown in FIG. 3, when two beams are spaced at

5 approximately 0.74 microns, which is the track pitch of DVD media, the two written marks actually coalesce into one large mark. This is an extreme case of the interference that can occur when two write beams are writing in very close proximity.

10 The effects of using more than two write beams is shown in FIG. 4, wherein three write beams are spaced 2.1 um apart, e.g. approximately triple the track pitch of a DVD-type optical disk. As shown in curve 46, the resulting pit spans nearly 4.0 um, or

15 five times the track pitch. The distribution shown in FIG. 4 can be determined from Equation (4), which is the superposition of three Green's functions.

$$G3(x,t) = G(x - d,t) + G(x,t) + G(x + d,t) \qquad (4)$$

FIG. 5 shows a plot of pit size versus beam

20 spacing for one, two, or three writing beams. From this graph it can be determined that a minimum spacing of about 3.8 µm is needed so that the width of a pit when writing with three beams is the same size as when writing with a single beam. When using more than three

25 writing beams, e.g., 5 or 7 beams, the minimum spacing will be larger than 3.8 µm. However, the difference should be small because the effect of the beams diminishes quickly with distance from the central beam.

The astute reader will realize that the

30 calculations presented above disregard the time-dependent effects caused by rotation of the optical disk. However, the figures are in good qualitative agreement with the results of more detailed

calculations, which do take into account the time-dependent energy distributions for rotating disc media.

FIG. 6 shows the results of a 3D simulation of heat propagation on a typical DVD. The simulation used typical disk layer structure, laser power levels, and relative motion between the disk and writing beams. Lighter shades indicate higher peak temperatures. The top image shows the result of writing to two adjacent tracks, wherein the writing beams are side by side. As can be seen in the top image, nearby pits can merge if beam separation is inadequate. The bottom image shows the result when the writing means are aligned at an angle to the tracks to provide adequate separation.

Because the minimum beam spacing exceeds the track pitch of a typical optical disk, it is necessary in multibeam writing to dispose the beams so that they are spaced apart at a sufficiently large distance to prevent thermal interference. One technique is to line the beams up at an angle to the tracks as shown in FIGS. 7 and 8, wherein the angle α of the beam axis with respect to the track tangent satisfies the condition given in Equation (5).

$$\sin \alpha = k \frac{p}{d} \qquad (5)$$

where p is the track pitch, d is the desired spacing between adjacent writing beams, and k is the number of tracks between writing beams. For FIG. 7, the beams are writing to adjacent tracks, so $k = 1$; whereas in figure 8 the writing beams are writing to every other track, so $k = 2$. Additional arrangements of the writing beams may be used, such as two-dimensional arrays of writing beams, as long as sufficient spacing is maintained between adjacent writing beams.

An optical disk drive for writing to multiple
track of an optical disk is therefore, provided. While
preferred illustrative embodiments of the present
invention are described above, it will be evident to
5   one skilled in the art that various changes and
modifications may be made without departing from the
invention. For example, systems employing different
numbers of reading or writing beams, or having somewhat
different arrangement of lenses could be constructed.
10   It will therefore be understood that illustrative
embodiments are provided for purposes of illustration
and not limitation, and that the present invention is
limited only by the appended claims.